Fig. 1—This striking photograph of the Western Hemisphere was taken by Application Technology Satellite III. With even this "low-photographic-quality" resolution, cell texture can be used to delineate significant water masses. Actual visual delineation of Bénard cells is not needed here to map warmer-than-air ocean waters.

From space:

NEW TOOL FOR STUDYING OCEAN WEATHER

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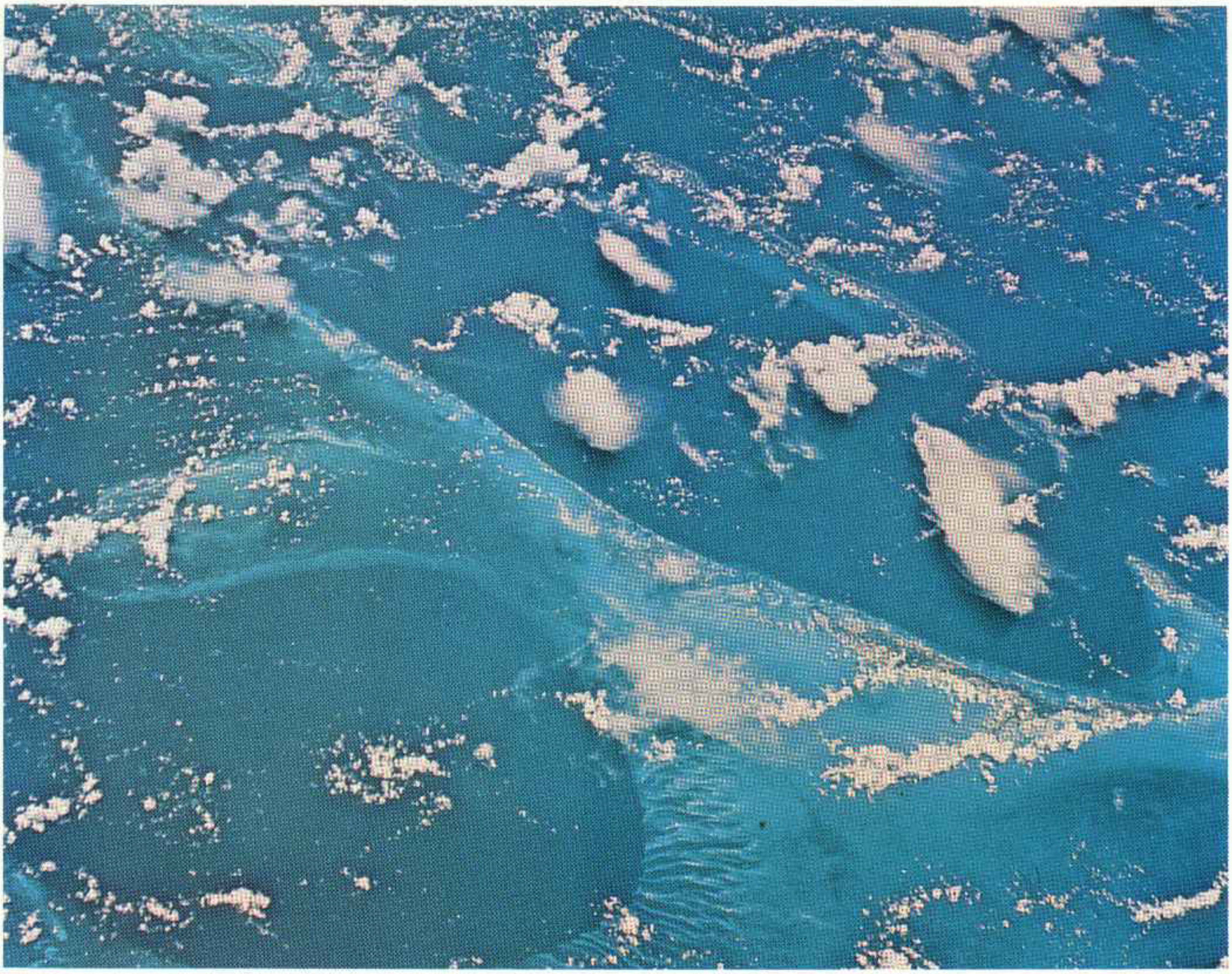

Fig. 2—Partially complete Bénard cells form over Great Exuma Sound and the open Atlantic east of Long Island, N.Y. Some cumuli have well-developed anvil heads; others show tops blown to the south. Most of the smaller ones, however, are arranged in a honeycomb pattern typical of tropical Bénard cells. (Photos taken by astronauts during several Gemini orbital missions.)

BACKGROUND

The natural organization of convective systems into simple cells was recognized by James Tyndall in 1863. Not until Henri Bénard (1900) conducted his classic experiments was there an understanding of the polygonal arrangement of the cells. He contributed to our knowledge of the phenomenon in publications that spanned the 37-year period 1900-36.

Bénard's studies were of microscopic systems, and from them was gained the empirical and theoretical recognition of the ideal hexagonal structure in fluid, air, or solid resulting from convection. It was Dusan Avsec (1939), however, who developed the fundamental principles and sequences of formation of polygonal convective cells from experiments with cigarette smoke in tiny cloud chambers. On the basis of photographs of stratocumulus clouds, he believed that such systematically arranged cells would occur in the earth's atmosphere. His evidence, however, was not convincing.

Malkus (1962) and Roll (1965) pointed out the probability that such cells would form in the tropical marine atmosphere. It was not, however, until photographs were taken by the astronauts of the Gemini program of the National Aeronautics and Space Administration that the occurrence of neatly arranged polygonal cumulus cells was verified (Fig. 2). The ready acceptance of the term "Bénard cells" for these spectacular atmosphere convective systems seems clearly justified.

Fig. 3—Over the Pacific near the Midway Islands, scattered cells spread across the sea north of Ocean Island, but most are poorly organized and disconnected.

Cells Over the Sea

THE REQUIREMENTS for the ideal development of Bénard cells over the sea are not different from those noted by Bénard and Avsec, or from the theoretical requirements, in part, noted by Schneck and Veronis (1967). The underlying surface (the sea) must be evenly heated with but a slight, if any, temperature gradient. The overlying marine atmosphere should not have significant horizontal motion (wind); should contain sufficient moisture to allow condensation to take place; and should be cooler than the sea so that suitable convection is established. Any deviation in one, or all, of these conditions results either in a modification of the cell structure from the ideal or in an absence of visible cells.

Clearly, the sea and the marine atmosphere never have the combination of the ideal conditions that can be attained in the laboratory. Nonetheless, Bénard cells in the marine atmosphere displaying the range of characteristics studied by Avsec have been photographed from Gemini spacecraft.

Cells which correspond to the early stages of formation were photographed repeatedly, thought not always in the early morning when incipient systems might be expected (Fig. 3). The lack of sufficient moisture or condensation nuclei, or both, can account for the low frequency of occurrence of incipient cells, especially where winds in the surface atmosphere are minimal. Such atmospheric conditions are not uncommon in the Pacific Ocean, particularly west of the Hawaiian Islands where such cells were seen with greatest frequency.

With sufficiently great sea-air temperature differences and suitable conditions for condensation, magnificent cells usually spread across the tropical seas each afternoon (Fig. 4). Every person who has sailed on, or flown over, such waters well remembers the cumulus growth through the day. No all, however, have recognized and appreciated the regular arrangement of the clouds.

That these diurnal waxing and waning clouds were not recognized as usually being organized into cells is understandable because of the cell diameter. Most are 10 to 30 km. across (Fig. 5) and even from an aircraft the perspective is poor for visualizing the cell structure. Now that these convective systems have been photographed from space, the typical arrangement and appearance of the cumulus clouds are so striking that they are easliy recognized even when the entire cell is not within the view of the observer (Fig. 6).

Sometimes, the cells attain proportions so large that even portions of the system may go undetected from a ship or an aircraft. Bénard cells of this magnitude were photographed over the Indian Ocean in September 1966 by the crew of Gemini XI (Fig. 7). Although the cells were not well distributed on this day, a few were well formed with diameters of 100 to 150 km. Those over the waters near the Laccadive Islands were nearly perfect.

Usually, convection over tropical waters is vertically unrestricted, in contrast to the complete restriction in the experiments conducted by Bénard and Avsec, in which a transparent top was placed on a cloud chamber to allow viewing of the formation and arrangement of the smoke. Normally no "top" would exist over the ocean. Consequently, the equilibrium or fully developed

Fig. 4—A nearly limitless expanse of well-formed Bénard cells are shown here over the north central Pacific. A clear cell pattern break is visible toward the right, seemingly caused by higher wind speeds and less convection.

Fig. 5—Early in the morning, astronauts aboard Gemini V passed over Mobile, Ala., and Pensacola, Fla. Surface winds are blowing smoke toward the coast. Seaward from the well-defined barrier beach, some poorly organized cells rise through a warm, moist, marine atmosphere.

Fig. 6—Segments of complete Bénard cells are seen as they appear from the Gulf of Mexico coast southeast of Galveston Island, Tex. Arrangement of small cumuli is indicative of typical honeycomb characteristic of Bénard cells.

Fig. 7—Small, light blue features beneath the streaky cirrus and the wide-spread Bénard cells are atolls of the Laccadive Islands, offshore India. Cloud-free skies surrounding the continent were the result of subsiding air as would occur during a daytime sea breeze. Later weather maps showed onshore winds along all coasts, with coastal air temperatures at about 80° F. Bénard cells were best formed over and northeast of the islands, and a few were nearly perfect hexagonals of the typical cumulus formation.

cells described by Avsec would not be expected; that is, the atmospheric cells would be open in the center.

Unrestricted vertical development of Bénard cells does take place over the tropical seas, except where cool waters are carried into the low-latitude oceans by currents. In such areas, where cool waters lie adjacent to, or flow into, warm waters, a temperature inversion is usual in the overlying atmosphere. This condition exists off southern California and Baja California where a strong current flows from north to south along the coast. The inversion acts as the "top" so that when other conditions are suitable, fully formed Bénard cells lie over the coastal waters (Fig. 8). The close association of closed and open cells in this photograph taken near Guadalupe Island is interesting. One would expect that the inversion height and the moisture content of the atmosphere were the same over the entire area. Differences in the temperature between the sea and the air are the remaining requirement for formation of the cells. The implication is, of course, that these open and closed cells lie over water of different temperature. There is, however, the clear possibility that the inversion does not cover the open cells.

Bénard and Avsec noted that when open cells were well-formed, and there was either a shear between the surface and the overlying air or a vertical shear, the cells would be deformed or stretched to an extent depending on the velocity difference across the shear. To the east of Guadalupe Island on November 13, 1966 (the left side of Fig. 8), a wind of more than 20 km./hr. that blew to the south caused the north-to-south deformation of the open cells. Such systems, showing deformation of all magnitudes, were photographed over the tropical oceans many times from the Gemini capsules.

Cells and the Space System

Much concern has been expressed about the effect of the inevitable clouds which prevail in the marine atmosphere on the view of the ocean from space and on the utility of remotely sensed data to oceanography. At any given time, much of the marine atmosphere contains clouds. Many of the cloud systems originate from cyclonic disturbances, especially in the mid and high latitudes. As a consequence, much consideration has been given to the use of remote sensors that "see" the sea surface regardless of the humidity or cloud conditions of the atmosphere.

Surely the presence of clouds hinders the view of the ocean, particularly in the visual and infrared portions of the spectrum, and thereby reduces the capability of determining water color and temperature. Often, however, the clouds are formed by interaction with the underlying water. Consequently, the occurrence of such clouds is of greater value than it is a hindrance.

Bénard cells are cases in point. They indicate that the water is warmer than the overlying air, but the amount of the temperature difference cannot be determined by their distribution. As a matter of fact, the conditions under which these convective systems form into visible cumulus cells are not precisely known. Nonetheless, the cells and their shapes provide information on (1) the relative difference in sea-air temperature, (2) the relative speed of the wind over the sea, (3) the distribution of the wind field, (4) the distribution of water temperatures, (5) the relative moisture content of the marine atmosphere, and (6) the general state of the vertical temperature gradient in the marine atmospheric layer. Though not actually quantitative, this is a great deal of usable information. Bénard cells, even in our present state of ignorance, are significant features, therefore, to be viewed from space.

An actual visual delineation of the cells probably is not necessary to map the waters that are warmer than the air (Fig. 1). Consequently, even the lack of photographic-quality resolution does not hinder the use of "cell-texture" to delineate significant water masses. In the Application Technology Satellite-III (ATS-III) television imagery of Nov. 19, 1967, the Atlantic ocean equatorial current is defined by a "texture" which surely is from Bénard cells, but the cells are not outlined clearly. The warm tropical waters can be seen to spread north and south from the eastern extremity of South America. To the north, they surge into the Caribbean sea; to the south, into the huge, counterclockwise system southeast of Brazil.

The daily delineation of these water and air-mass transports is clearly suitable as a first analysis of the hemispheric exchange of heat energy. Just as clearly, data from satellites like ATS-III aid in the evaluation of the energy budget, but are not a panacea.

And, among all the considerations, prognostications, and ruminations, we can recognize cloud systems that are direct results of sea-air interaction, as Bénard cells are, and that facilitate the understanding of the ocean as viewed from space.

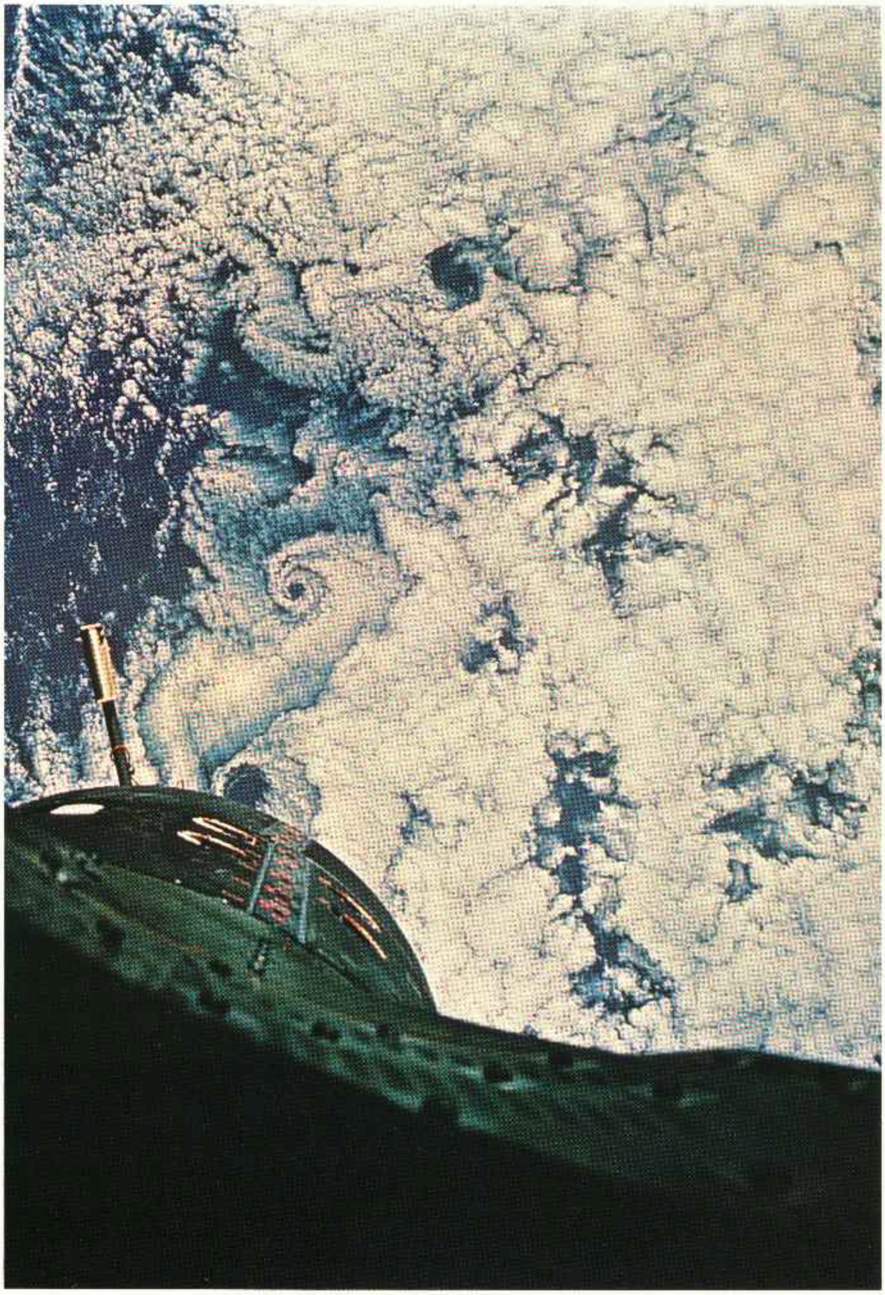

Fig. 8—South of Guadalupe Island off Baja California, von Kármán vortices and an interesting collection of Bénard cells appear. The island is hidden by the spacecraft's nose, but cyclonic halves of the vortices are clearly seen downwind. Closed Bénard cells are well formed seaward and south of the island, with some intermingled open cells. East of the vortices, toward Baja California, a fine series of sheared cells indicates winds of higher speeds than those farther offshore.

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Note: This paper is Contribution No. 267, Bureau of Commercial Fisheries Biological Laboratory, Galveston, Texas. ■